THE ROLE OF GPS IN PRECISE EARTH OBSERVATION

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ABSTRACT

The Global Positioning System is already having an important impact in earth science and its role will increase dramatically in the coming years. The greatest sucess to date has been in the precise measurement of vectors between observing points on earth for studies in solid earth dynamics. Accuracies of 1-2 parts in 10^8 are now consistently achieved over distances of a few hundred to 2000 km—sufficient to observe plate motion over 1 year. Soon GPS will be exploited to track remote sensing satellites with sub-decimeter accuracy. The first will be Topex/Poseidon, a US/French ocean altimetry mission to be launched in 1991. Developments planned for future platforms may push orbit accuracy near 1 cm within a decade. GPS receivers on some platforms will track the signals down to the earth limb to observe occultation by intervening media. This will provide comprehensive information on global temperature and climate and help detect the possible onset of a greenhouse effect. Dual frequency observations will be used to trace the flow of energy across earth systems through detection of ionospheric gravity waves, and to map the structure of the ionosphere by computer tomography.

INTRODUCTION

As deployment of the Global Positioning System's operational satellites gets underway, efforts to exploit GPS for earth science are coming into sharper focus. Some of these activities have taken new directions, away from the familiar positioning and navigation functions of GPS into areas of direct earth observation. The most widely known GPS earth science applications are precise orbit determination of remote sensing satellites, primarily ocean altimetric satellites, and direct measurement of earth baselines for studies in solid earth dynamics. In the mid-1980s we saw the development of specialized GPS-based techniques to determine the orbits of low earth satellites with sub-decimeter accuracy(1-3). These will see their first full-scale demonstration on Topex/Poseidon, the joint US/French oceanographic satellite set for launch in late 1991. We have recently seen techniques for GPS-based measurement of earth baselines refined to deliver accuracies of 1-2 parts in 10^8 over distances up to 2000 km(4-6). That translates into baseline accuracies of 1-3 cm for the longer baselines and better than 1 cm for regional baselines of under 1000 km. This allows us to observe tectonic plate motion on a time scale of one year and is comparable to the accuracies currently achieved by more cumbersome very long baseline interferometry (VLBI) and satellite laser ranging (SLR).

Even this performance, however, will not satisfy the coming needs of geodynamics and ocean science. At a recent workshop on The Interdisciplinary Role of Space Geodesy, held in Erice, Italy, panels of scientists and engineers set down long term objectives for a number of areas of earth science(7). Two of the Erice recommendations will be important drivers of precise positioning and navigation technology for years to come. The panel on ocean physics established an accuracy goal of 1 cm for continuous geocentric altitude knowledge of ocean altimetric satellites; the panel on solid earth physics set a goal of 1 mm accuracy for regional land-based geodesy. These goals pose a formidable challenge to all relevant technologies. We believe, however, that with the aid of some creative engineering they will be within the capabilities of GPS in the next decade.

In 1987 a group at the Jet Propulsion Laboratory undertook an initiative that may help to achieve these goals by exploiting GPS receivers to be placed on several science platforms in the mid and late 1990s. The objectives of this effort have recently been expanded to include new investigations in geodynamics and atmospheric and ionospheric science, and the team has been joined by other groups at JPL, the California Institute of Technology, and the University of Illinois. Opportunities for atmospheric and ionospheric science will be created by tracking GPS satellites from orbiting platforms as the signals are occulted by the intervening media. The full investigation will encompass precise orbit determination, with a goal of 1-3 cm accuracy for each platform; studies in solid earth dynamics, with a focus on the redistribution of strain following major earthquakes; examination of long term trends in global climate, searching for definitive signs of the onset of a global greenhouse effect; studies of the origin and propagation of acoustic gravity waves in the atmosphere and ionosphere; and 3-dimensional mapping of localized ionospheric structures, such as equatorial bubbles and the mid-latitude trough, by computerized tomography.

GENERAL BACKGROUND

Baseline Measurement with GPS

Precise observation of GPS signal delay and/or delay rate between receiving points on earth enables precise measurement of the baseline vectors between those points. Accurate knowledge of the GPS satellite orbits is essential for an accurate baseline solution. In the early 1980s what has come to be known as the "fiducial concept" was developed to address GPS satellite orbit error in geodetic measurements(4,5). A precisely known regional network of reference receivers (fiducial sites) observes the GPS satellites along with receivers at other points of geodetic interest. With the fiducial sites held fixed, all GPS satellite orbits and the "mobile" receiver positions are simultaneously adjusted using an extended arc of data. Orbits and baselines are thereby obtained in the reference frame defined by the fiducial network. For highest accuracy, a "dynamic" solution is used requiring accurate modeling of receiver and GPS satellite motion over many hours. Fiducial accuracy is transferred to the mobile sites; the resulting GPS orbit errors scale in proportion to distance. U.S. fiducial networks, established by years of VLBI observation, are now accurate to 2-4 cm, enabling comparable accuracies in continental baseline measurements and sub-meter GPS orbits.

Topex Precise Orbit Determination (POD)

In 1982 we began looking for new ways to track Topex, proposed for radar mapping of ocean topography with a precision of ~2 cm. To separate orbit variations from ocean topography, continuous determination of orbiter geocentric altitude with an accuracy approaching that of the altimeter is desired. A goal of better than 10 cm geocentric altitude accuracy was set—a five-fold improvement over performance on Seasat, the Topex predecessor. The technique that emerged was a simple analogue of the GPS fiducial concept. In this variation, a GPS receiver is flown on the orbiter, which takes on the role of a mobile site, and the ground network is extended globally. NASA's Deep Space Network (DSN) sites in California, Spain, and Australia will serve as fiducials, defining a reference frame known geocentrically to a few centimeters; three complementary sites will fill out the reference network. Using several hours of data we solve for all GPS orbits and mobile receivers, which now include the one aboard Topex. To overcome the formidable problem of modeling the motion of a complex low-orbiting platform, in 1985 we proposed a non-dynamic strategy exploiting the unique properties of GPS(1). This kinematic technique dispenses with platform motion modeling (though retaining it for the ground sites and GPS satellites), relying instead on smoothed geometric positioning. Studies show that kinematic tracking can achieve sub-decimeter accuracy regardless of orbiter dynamics—as readily for the space shuttle as for Topex.

POD in Earth Science

We can illustrate the value of precise orbit determination to ocean altimetry with an example from the study of basin scale ocean circulation. Ocean gyres are key features of ocean circulation that are believed to wobble on a scale of thousands of kilometers with an amplitude of a few centimeters. Quantifying this variability is essential to understanding ocean circulation dynamics and the ocean-atmosphere interaction. Such observations are impossible with current altimetric data and Topex will just begin to achieve the needed accuracy. Centimeter POD will enable future altimetry missions to improve observations of basin-scale ocean variability and extend Topex results to interannual and even decade periods, leading to a better understanding of the interplay between the oceans and atmosphere.

Centimeter accuracy will also be valuable in calibrating biases in precise altimeters. GPS-determined altitude, for example, can be compared against altimetry over regions of known elevation, such as lakes and deserts. Where the elevation is not known, a GPS receiver placed on the surface will provide a platform-to-ground baseline that can be determined continuously. This technique, using receivers on ocean platforms, is now being developed for calibrating the Topex altimeter. A more novel application of decimeter tracking is in the construction of interferometric SAR images with data from a single SAR element. In a technique pioneered by Goldstein with data from Seasat(8), SAR images from repeat ground tracks can be combined to provide 3-dimensional information—so long as the relative platform positions between passes can be determined to much less than a wavelength. This can be done with a costly fringe-searching process (as with Seasat) or directly with decimeter position knowledge. Only the latter is suitable for volume production.

Direct Science from GPS

Topex POD studies yielded an unexpected insight that, in a sense, completed an evolutionary circle: Orbiting GPS receivers can markedly improve the measurement of earth baselines and point positions over short time spans. They do this by strengthening GPS orbit determination, serving as intermediate observing points between widely separated ground sites having poor common GPS visibility, extending the vertical viewing geometry for all baselines, and desensitizing the solution to media effects by introducing measurements with no intervening atmosphere. It soon became apparent that even without a POD task to perform, orbiting GPS receivers should be part of a robust GPS-based geodetic system. The precise positioning capabilities of GPS can thus serve at least 3 earth science interests: altimetry, SAR interferometry, and space geodesy. With some care in system design, we can also acquire valuable earth science data of a quite different kind.

The orbiting receiver field of view, a zenith-directed hemisphere on Topex, can be extended to the earth limb to improve tracking accuracy and to observe signal occultation by the atmosphere and ionosphere. Radio occultation experiments have a more than 20-year history in planetary science. Variations in signal phase and amplitude during planetary occultations of spacecraft are used to construct profiles of density, pressure, and temperature, and to analyze the composition and turbulence of planetary atmospheres(9). Until now we have not had the comprehensive satellite-to-satellite links needed to apply these techniques usefully to Earth. The abundant raypaths from 24 GPS satellites to an assortment of low orbiting platforms will soon provide that opportunity. Lateral sampling of the atmosphere and ionosphere will extend the earth coverage of remote platforms and yield valuable data on geophysical processes ranging from decade and longer changes in global climate to evanescent atmospheric waves. We now discuss these principles and applications in more detail.

GPS-BASED POD & PRECISE GEODESY

GPS Principles of Operation

The GPS satellites transmit carriers at 1575 and 1227 MHz. Each carrier is phase modulated by a precise ranging code consisting of pseudorandom bit sequences at 10.23 Mbs. The transmit time, as kept by the clock onboard each GPS satellite, is precisely known for each bit in the sequence. A GPS receiver identifies the incoming code bits and measures their arrival time, as kept by the receiver clock. The difference between the known transmit time and observed arrival time is a measure of the range between the satellite and receiver plus the time offset between transmitter and receiver clocks, a quantity known as "pseudorange". A receiver measuring pseudorange to four satellites can instantaneously determine its three components of position and its time offset from GPS time, typically with an accuracy of 10-15 m. Many receivers can also measure and keep continuous count of carrier phase with a precision of better than 1% of a wavelenth (<2 mm) in 1 sec. Continuous phase can be used to construct a record of position change with centimeter precision.

POD & Precise Geodesy

Positioning error drops markedly in relative or differential applications in which a receiver location is determined with respect to one or more known reference sites observing GPS at the same time. Virtually all clock errors are removed by differencing or direct solution and the effect of GPS orbit error is reduced by common mode cancellation. Instantaneous relative position error, typically 1-2 m, can be improved by smoothing observations over extended intervals (reducing random error) and solving for key geometric and other parameters (reducing systematic error). This is simply a restatement of the fiducial concept. The geometric parameters include all GPS orbits, the user position (or orbit), and all ground sites except a minimal reference set. Additional dynamic and observational parameters, such as tropospheric zenith delay and solar radiation pressure, may be adjusted as well. The technique can accommodate any number of "user" receivers on the ground or in orbit; indeed, the more users, the stronger the global solution. Thus a single system provides the mutually reinforcing functions of POD and precise geodesy. Direct and differential positioning are depicted in Fig 1.

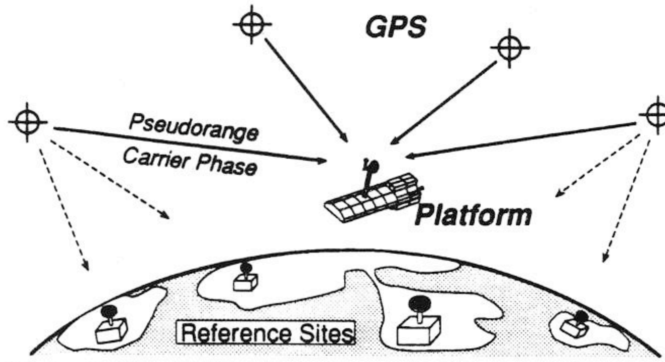

Fig 1. In direct GPS-based tracking, user observations alone determine user position with respect to GPS. In differential tracking, user and ground observations determine user, GPS, and some ground positions with respect to a fixed ground reference network.

POD for low earth orbiters with all tracking systems except GPS (and, when operational, the Soviet Union's GPS-like Glonass system) must rely on one basic technique: dynamic orbit fitting. GPS, uniquely, offers a versatile alternative in the form of precise geometric positioning combined with kinematic smoothing, as well as a synthesis of the kinematic and dynamic techniques which is more powerful than both.

Dynamic Orbit Fitting

Long arc orbit fitting has classically been a dynamic process: A model orbit, constructed analytically from an approximate initial state by integrating the equations of motion, is fit to the tracking measurements by least squares adjustment of a limited set of parameters, typically the satellite epoch state (position & velocity at the start time) and a few others. Random measurement noise is thereby smoothed against an orbit model. The quality of the dynamic solution is critically dependent on the quality of the force models used to generate the orbit model—an accurate solution requires accurate models. In applications seeking few-decimeter or better POD, such as Lageos, Seasat, and Topex, extraordinary effort has been expended refining models for gravity, drag, radiation pressure, and the like. For Lageos, a dense sphere at an altitude of more than 5000 km, decimeter modeling is now readily achieved. For Topex, at 1334 km where gravity error is worse, decimeter modeling may be within reach, but only with a good deal of model refinement. For future missions, such as the large polar orbiters of the Earth Observing System (Eos) proposed to fly at 824 km, increased drag and gravity error, massive slewing instruments, and uncertain center of gravity (CG) will make decimeter modeling exceptionally difficult; gravity error alone may initially be at the meter level. And for the sprawling space station at 400 km, with severe drag, roving astronauts, and so on, dynamic POD is far out of reach.

Kinematic POD with GPS

GPS offers two features that enable a fundamentally different approach: continuous coverage by four or more satellites, providing uninterrupted geometric position determination, and continuous phase and range data types to enable long term kinematic smoothing. Because this technique does not use the laws of motion to infer position, knowledge of the changing platform CG is not needed; instead position is referred to a fixed point on the GPS antenna, calibrated with 1-mm accuracy with respect to antenna phase response.

Kinematic POD is illustrated in Figs 2a-c. A sequence of N independent position solutions (either direct or differential) obtained from pseudorange is shown in Fig 2a. The dashed line represents the true satellite motion. Figure 2b shows the record of position change obtained from carrier phase over the same arc. In differential tracking, position change error is at the centimeter level, about two orders of magnitude smaller than the position error. The track of position change can now be fit to the position points by adjusting a 3-dimensional position bias to minimize the mean square residual between the two sets of points. The adjusted track of position change settles in at the mean of the position points, smoothing them over the entire arc. The resulting smoothed trajectory as shown in Fig 2c. By this technique, a 1 m instantaneous position error can in principle be smoothed to 10 cm in a matter of minutes.

Reduced Dynamic Tracking

The kinematic technique discards all platform dynamic information in order to eliminate dynamic modeling error. Often, however, there will be some dynamic information which, if properly weighted, will improve the kinematic result. A simple Kalman filter formulation developed in 1986 combines dynamic and kinematic information in a completely general way, allowing arbitrary relative weighting(3). In this technique the filter is augmented with process noise on the force model. Increasing the sigma on the process noise increases the kinematic component of the solution. With sufficiently large sigma the solution becomes purely kinematic; with zero sigma it is purely dynamic. Properly weighted this *reduced dynamic* strategy must always equal or surpass both dynamic and kinematic tracking alone. For dynamically unpredictable platforms like the shuttle or space station, dynamic information will be too weak to offer any real improvement. For quieter craft like the Eos polar orbiters, deweighted dynamics will be helpful. Because the dynamic characteristics for these platforms are not yet well known, the error analyses presented in the next section employ the more pessimistic kinematic approach.

In 1986 we presented analyses indicating that both the kinematic and reduced dynamic techniques could achieve altitude accuracies of a decimeter or better with the GPS configuration to be used for Topex(2). For Eos and the space station we now propose an extended configuration that could bring performance near 1 cm in all components. Key changes include extension of the flight receiver field of view down to the earth limb; increased flight receiver tracking capacity from five to twelve satellites; expanded ground network from six to ten sites; and improved measurement precision based on JPL's new Rogue receiver(10).

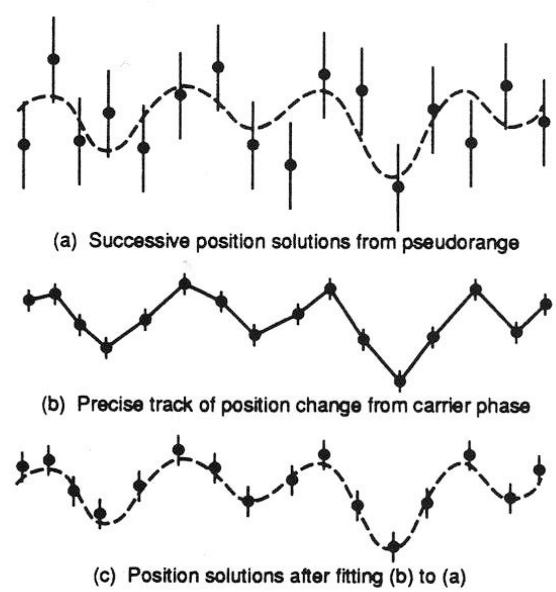

Fig 2. Conceptual illustration of GPS-based precise position determination through kinematic smoothing.

Performance will also benefit from improvement in our knowledge of the DSN reference sites from the 5 cm assumed for Topex to about 2 cm by the mid-1990s, and from the expansion of the GPS constellation to 24 satellites. Further improvement is gained by extending the solution arc to 8 hours from the 2-4 hours used in most Topex studies. POD and ground baseline error analyses for this configuration are presented below.

POD and Geodetic Error Analysis

Detailed simulation and covariance studies have been carried out for kinematic tracking of Eos and the space station, as well as for ground site geocentric position solutions and both regional and global baseline solutions. All studies assumed a 10-site ground network, with the three DSN sites defining a fixed reference frame and seven supplementary sites that were adjusted in each solution. The regional geodetic studies supplemented the global network with several North and Central American sites. To assess the role of orbiting GPS receivers in ground-based geodesy, all geodetic studies were performed both with and without orbiter data. Receiver performance assumptions used in the studies were consistent with the current performance of the Rogue receiver. Strong observing geometry and high data volume are critical in kinematic POD, hence the assumption of 12-satellite tracking capacity and full sky visibility. (With 24 GPS satellites and full sky coverage the platforms can see between 13 and 17 satellites at all times.)

Predicted orbit accuracy does not differ significantly between the polar and manned platforms, despite their differing orbits and dynamics. (The space station orbit will be inclined at 28.5°, the polar platforms at 98°.) Typical 2-, 4-, and 8-hour results are shown in Fig 3. Predicted rms accuracies over the arcs are about 3 cm (each component) in 2 hrs falling to 1.3 cm in 8 hrs. Because of the limiting effects of troposphere, fiducial error, and carrier phase measurement error (which is not reduced in kinematic smoothing), there is little reduction beyond 8 hrs.

Figure 4 shows the predicted absolute position errors for several adjusted sites of the network using a 2-hr data arc under two assumptions: no orbiting receivers and two orbiting receivers (1 Eos, 1 space station). The orbiters provide a factor of 2-to-4 improvement, bringing performance down to the scientifically interesting 1-3 cm level. These results are for point positions in the frame defined by the three NASA Deep Space Network sites. Figure 5 shows a similar comparison for long baselines (4000 to 12500 km) between various of the adjusted sites. The error decreases with increasing arc length. At 8 hours (not shown), all

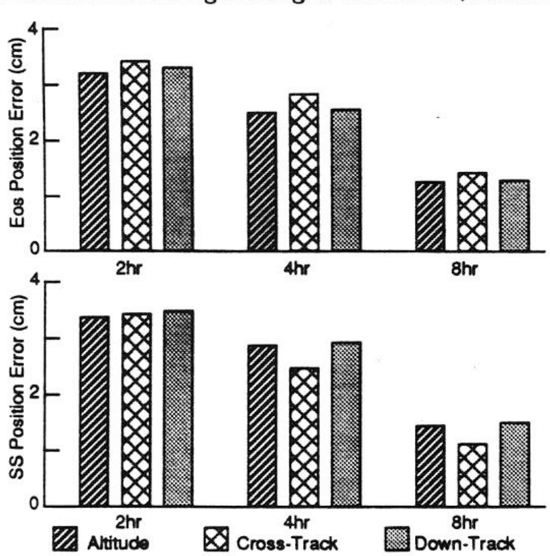

Fig 3. Covariance analysis of Eos and space station kinematic POD.

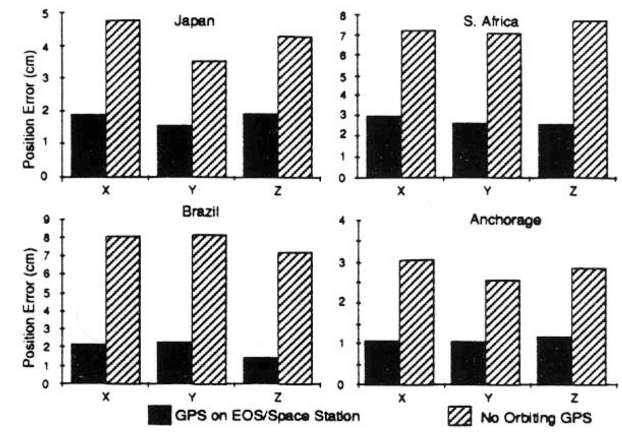

Fig 4. Covariance analysis for global point positioning with and without GPS receivers on 1 Eos and 1 space station (2-hr arc).

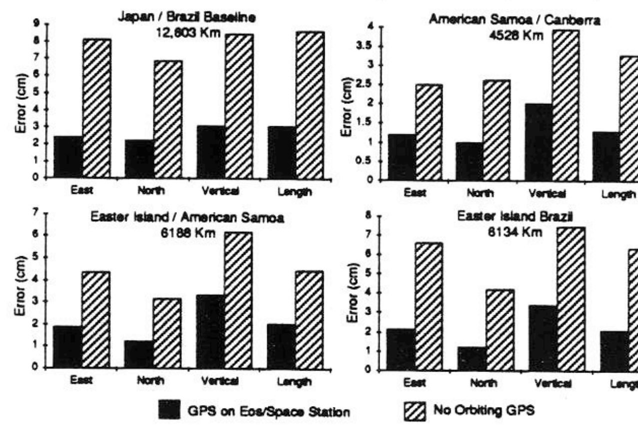

Fig 5. Covariance analysis for long baseline geodesy with and without GPS receivers on 1 Eos and 1 space station (2-hr arc).

baseline and point position errors are less than 1.5 cm. If fewer ground sites are assumed, the advantage with orbiting receivers is more dramatic. In an extreme example, with four sites, no solution is possible without the orbiters since there is no common GPS visibility between site pairs; with the orbiters added, solutions reach 2-3 cm within 2 hrs.

A study for regional geodesy examined baselines ranging from 250 to nearly 5000 km in North and Central America and the Caribbean. Figure 6 shows the predicted errors for the N-S and vertical components as a function of baseline length, using a 4-hr data arc both with and without two orbiters. The orbiter advantage increases with baseline length. Significantly, the error

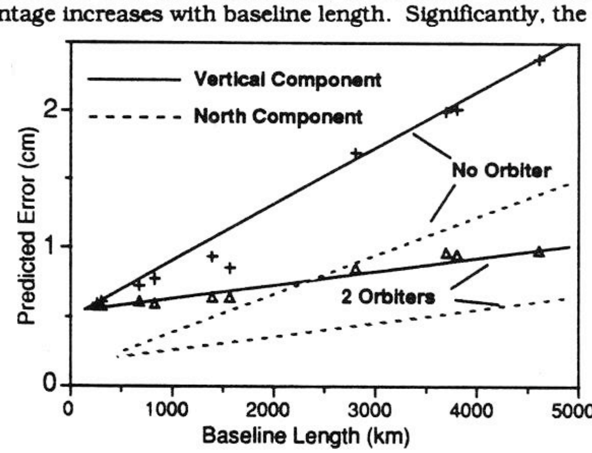

Fig 6. Covariance analysis for regional geodesy with and without GPS receivers on on 2 polar platforms (4-hr arc).

in the vertical, which is always the most difficult to recover with upward-looking GPS measurements, falls below 1 cm for even the longest baselines. When the arc length is extended to 8 hrs, the accuracy of all components improves to 5 mm or better.

Recent Experimental Results

Understandably, theoretical performance claims like these are often met with skepticism (and worse). Since it will be several years before we can work with data from real orbiting receivers, it may be helpful to review recent results in purely ground-based GPS geodesy. In 1985-86, three North American geodetic experiments using the current 6-satellite GPS constellation were carried out jointly by about 20 institutions(5,6). Each experiment lasted 1-3 weeks and deployed 10-20 TI-4100 geodetic receivers across the continent. In data analysis at JPL, 3 or 4 well-known sites were designated fiducials and solutions for GPS orbits and baselines ranging in length from less than 100 km to more than 2,000 km were repeatedly performed. Error studies taking into account the limited constellation and modest receiver capabilities had predicted baseline accuracies of 2-3 cm over 200 km (~1 part in 10^7) and 7-12 cm over 2000 km (~5 parts in 10^8). Performance was evaluated by the repeatability of independent baseline measurements over many days (precision) and by absolute agreement with historical VLBI measurements (accuracy).

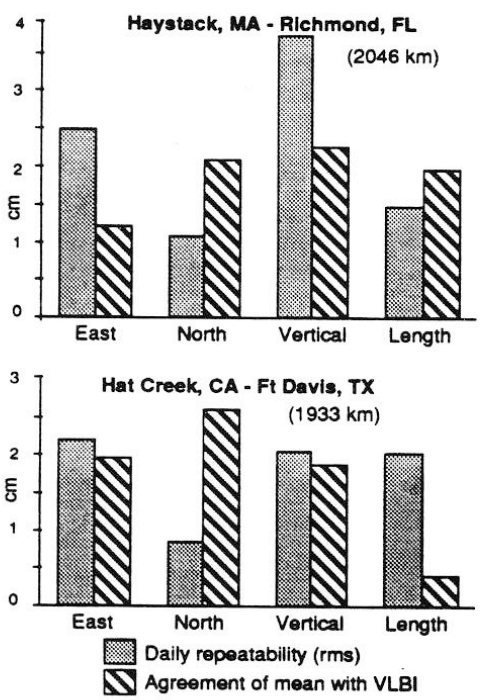

Fig 7. GPS-based determinations of ~2000 km baselines. Graph shows daily repeatability and agreement with VLBI. Geometry for MA-FL solution was relatively poor. Data were taken over 2 weeks in Nov 85.

Through processing refinements developed in the course of data analysis, such as the introduction and tuning of stochastic process noise models for tropospheric effects and solar radiation pressure, several errors were reduced well below predictions. We now consistently achieve both daily repeatability and absolute agreement with VLBI of 1 cm or better in the horizontal components up to distances of 1000 km, and 1-3 cm for distances of 2000 km. Figure 7 shows the repeatability and the agreement with VLBI in a recent solution for two long baselines using data taken over 2 weeks in Nov 85. (The western baseline had stronger observing geometry.) GPS orbit errors, determined by comparisons between solutions using independent data, are typically 20-70 cm per component for well-tracked satellites(5,6).

New receivers offer far better measurement accuracy than those used in 1985-86. The Rogue receiver achieves a pseudorange precision of 10-15 cm in 1 sec, and a multipath peak typically less than 5 cm after 30 minutes of smoothing. Carrier phase precision is sub-millimeter. These are nearly 10-fold improvements over the levels of the 1985-86 experiments and will lead directly to improved baseline results. The present results nevertheless tell us a good deal about the likely performance of kinematic orbit determination. Because kinematic tracking does not introduce new dynamic errors into the solution, the kinematic error *sources* will be virtually the same as the error sources in ground-based geodesy. The *sensitivity* to those error sources will change in a predictable way revealed accurately by covariance analysis. As these error sources are now very well understood, we can have considerable confidence in the POD error predictions.

Geodynamic Science

Though we have not, at this writing, seen deployment of the first Block 2 GPS satellite, ground-based GPS geodesy has become a mainstay in geodynamic science and its use is rapidly expanding. A principal science application is the measurement of crustal plate motion and deformation. Key geophysical questions center on the complex crustal dynamics in regional deformation zones and at plate boundaries. Large scale plate motions are fairly well understood from the geological record, although a good deal of work is also going into confirming and refining global tectonic models. Plans are currently being drawn up to apply GPS techniques to the observation of sea floor spreading by acoustically linking GPS receivers mounted on rigid ocean platforms to transponders anchored to the sea floor. The trend in ground-based geodetic technology is toward a permanent global observing network, perhaps a dozen sites, to provide accurate tracking of GPS satellites, supplemented by high density networks in regions of high tectonic activity such as Southern California and Chile. The network will operate semi-autonomously, providing an unbroken record of global and regional deformation.

The advent of high performance orbiting receivers in the latter 1990s will improve both the accuracy and time resolution of geodetic measurements. Sub-centimeter accuracy over distances up to 5000 km will be achievable with a few hours of observation. This will permit direct measurement of the rapid redistribution of strain following large earthquakes, information that is critical to understanding the earthquake process and that at present is often impossible to obtain. Preliminary studies indicate that GPS will also be valuable in observing polar motion, the earth rotation rate, the location of the geocenter, and the variations of these in response to major earthquakes(11-13). Receivers on drag-compensated low orbiters can help improve models of the earth's gravity field and may reveal gravitational time variations due to such processes as post glacial rebound, plate motion, and the changing distribution of atmospheric mass. All of these can contribute to our understanding of the structure and dynamics of the earth; however, a great deal of analysis is needed before we will understand the full role of GPS in many of these areas.

GPS OCCULTATION SCIENCE

In contrast to the burgeoning field of GPS geodesy, science through GPS signal occultation has been little explored. Recently we attempted to identify some of the potential science payoffs of GPS occultation measurements. Three promising areas came to light: atmospheric temperature profiling, acoustic gravity wave analysis, and tomographic mapping of the ionosphere. Since NASA intends to navigate the two Eos polar platforms and the space station by GPS, it is convenient to assume those platforms, flying concurrently, as bases for occultation measurements. For ionospheric mapping it is also helpful to include measurements from the ground and from down-looking platform instruments.

Global Climate & The Greenhouse Effect

When a radio signal is occulted by the atmosphere its phase and amplitude are perturbed in a manner related to the vertical refractivity profile, N(h), where h is altitude(9). Phase perturbations reveal refractivity, from which we can determine density, pressure, and temperature. The analysis requires computing the ray asymptote miss distance (a) as a function of the ray bending angle (α), as illustrated in Fig 8. These are given by the spacecraft ephemeris and the Doppler frequency observed on the link. The refractive index distribution is found from a(α) by solving an Abelian integral equation(9). With GPS L-band data we must form the dual frequency combination of carrier phase to remove the effect of the earth's ionosphere. True atmospheric refractivity profiles can then be computed and used to analyze the thermal structure of the stratosphere and troposphere, below about 50 km. The process involves 3 steps: First we compute the vertical number density profile from each refractivity profile; next we compute the vertical pressure distribution by assuming hydrostatic equilibrium and integrating the air density from the top of the atmosphere downward to the surface; finally we form the temperature profile from the number density and pressure profiles using the equation of state.

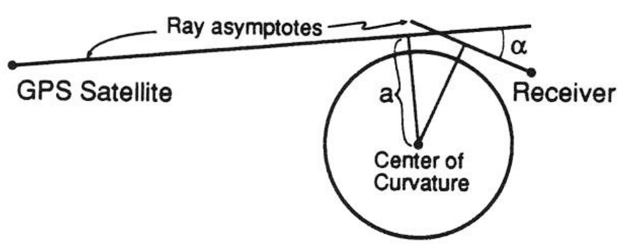

Fig 8. Ray asymptotes during GPS signal occultation.

Vertical resolution, determined by the limits of geometric refraction, will range from ~0.5 km near the surface to ~1 km near the top of the stratosphere. Temperature accuracy will depend on several factors. In the middle and lower atmosphere random measurement error is a small fraction of total refractivity; systematic errors in modeling platform motion and in removing Doppler bias will dominate. Thus, precise navigation during the observation is critical. At the tropopause (about 12 km), temperature accuracy will be 0.1-0.4 K, with the random component <0.1 K. The error will grow gradually with altitude until loss of refractivity in the thinning atmosphere causes random error to dominate. The major sources of random error will be short term

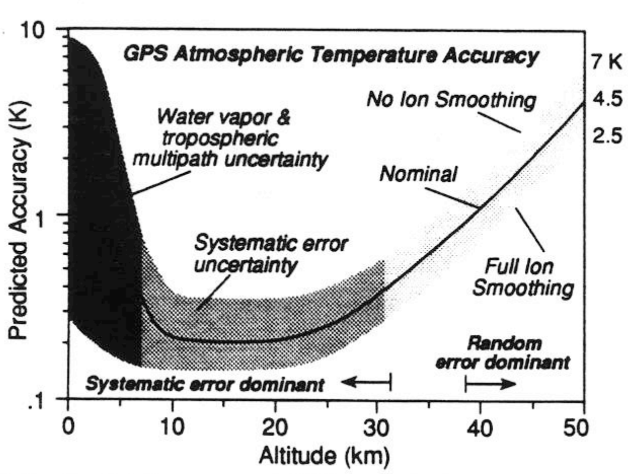

Fig 9. Predicted accuracy of GPS atmospheric temperature measurements with areas of uncertainty highlighted.

phase instability in the GPS satellite cesium oscillators and thermal noise in the receivers. (Receiver oscillator instability can be differenced out.) The GPS oscillators will contribute an error comparable to or less than thermal noise.

We incur a thermal noise penalty of about a factor of 3 from the dual frequency ionospheric calibration. This penalty can be reduced by smoothing the ionospheric correction. The final thermal noise level will depend on the degree of ionospheric smoothing we can achieve, which in turn depends on the behavior of the ionosphere. Figure 9 gives the predicted temperature accuracy envelope bounded by various uncertainties. This performance surpasses the published Eos science and observational requirements for temperature in the troposphere (1 K required/0.5 K desired), middle atmosphere (2 K/1 K) and upper atmosphere (10 K/5 K), and compares favorably with accuracies quoted for specialized, dedicated atmospheric sensors.

We know that the long term climate on earth is governed by a balance between the absorbed solar radiation and the emitted infrared radiation. Models of the terrestrial atmosphere and surface indicate that observed increases in the concentrations of carbon dioxide, methane, chlorofluorocarbons (CFCs), and other trace gases should produce a greenhouse effect at the surface, leading to a significant increase in average global temperature and a consequent melting of polar ice and a rise in ocean levels(14). In the stratosphere, these models predict a lower air temperature because of increased radiative cooling. A doubling of the carbon dioxide concentration may decrease the temperature in the stratosphere by as much as 10 K. The stratospheric temperature may also drop because of reduced absorption of solar radiation in the ozone layer brought about by ozone depletion resulting from widespread use of CFCs. We cannot yet tell whether the predicted greenhouse effect has started, or whether recently observed changes in atmospheric temperature and composition herald a long term trend. Long term global coverage provided by GPS occultation measurements, and other orbiting atmospheric instruments, will provide a comprehensive picture of atmospheric thermal structure and composition, and will enable the earliest possible detection of the onset of fundamental (and potentially devastating) climatic changes.

Ionospheric Tomography

Irregular structures of different sizes are generated in the ionosphere as a result of its electromagnetic, corpuscular, and dynamic coupling with the magnetosphere, and its dynamic and aeronomic interactions with the thermosphere and middle atmosphere. The ionosphere, in short, is a complex, highly mutable matrix containing an assortment of transient, inhomogeneous features. To begin to understand it we need an accurate physical description of its different features and the ability to follow their evolution in time and space. Over the years, many observational techniques have been devised for this purpose. One of the most important of these is the measurement of total electron content (TEC) along a path of given cross-section.

With a simple linear combination of dual frequency GPS data we can continuously measure TEC along all GPS-to-receiver raypaths. Pseudorange by itself will give absolute TEC with an accuracy of about 10^{16} electrons/m^2 (16 cm delay accuracy at L1) in 1 sec. Smoothing pseudorange against precise carrier phase will improve this to better than 10^{15} e/m^2 (<2 cm), or about 0.1% of the daytime zenith peak and 0.5% of the typical nighttime minimum. Continuous carrier phase measurements by themselves will give TEC change with a precision of better than 10^{14} e/m^2 (<2 mm). Down-looking TEC measurements will strengthen ionospheric sampling. The global coverage offered by the platforms and the GPS ground sites will provide an unprecedented examination of ionospheric structure and short term variability.

Ground-based multistation TEC data have often been used to study the horizontal variation of ionospheric structures. TEC data cannot, however, provide information on ionospheric variation along the path of observation using conventional analysis techniques. To obtain such information, our group at the University of Illinois recently introduced TEC analysis by computerized tomography or CT(15). CT is a technique whereby an image of an object is constructed from a set of projections, or integrated densities, taken along many lines through the object and is widely used in medicine to produce cross-sectional X-ray images. More recently, 3-dimensional acoustic and seismic tomography have been applied to the oceans and solid earth. In ionospheric tomography, the measurement of TEC along a raypath is the analogue of the integrated density registered by an X-ray. TEC measurements taken along many raypaths can be used to construct maps of electron distribution in 2 or 3 dimensions.

We have shown that with TEC data from an orbiting satellite collected by a linear array of ground receivers, it is possible to resolve features of a few tens of kilometers(15). Figure 10 shows the typical observing geometry used in these satellite-to-ground experiments. A major limitation on reconstruction with ground observations is that the vertical profile of the background ionosphere cannot be recovered. For that, horizontal observing paths through the structure are required—paths that will be abundantly provided by orbiting receivers. GPS receivers and down-looking instruments on three platforms, supplemented by ten ground sites, will provide an immensely rich data set for both regional and global ionospheric tomography.

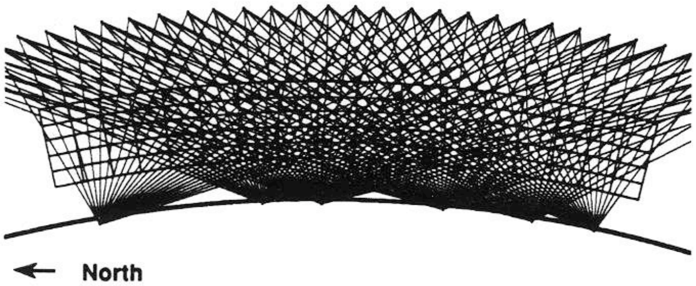

Fig 10. *Typical placement of pixels and rays for ground-based ionospheric CT experiments by team at the University of Illinois.*

Acoustic Gravity Wave Detection

Ionospheric waves called traveling ionospheric disturbances (TIDs) are the manifestation of acoustic gravity waves (AGWs) propagating in and intersecting with the ionosphere. AGWs are present at all levels of the atmosphere and have been detected by a variety of experimental techniques from the earth's surface to the ionosphere(16,17). AGWs can be caused by unusual events such as volcanic eruptions, earthquakes, and explosions in the atmosphere. A magnitude 7 earthquake, for example, will create a surface uplift of several centimeters over several hundred kilometers, launching an atmospheric gravity wave. We have calculated that upon reaching the ionosphere the gravity wave can temporarily increase TEC by $5x10^{15}$ e/m^2, or 8 cm of delay at 1.6 GHz—easily observable with millimeter-precision GPS carrier phase. In most cases, however, atmospheric waves have their origin in meteorological and geophysical events such as strong wind shear, distortion in jet streams, convective storms and fronts, and auroral-related high latitude events.

Once generated, gravity waves carry energy and momentum from the source to other parts of the atmosphere. As they ascend through the thinning medium the particle motions are amplified through conservation of energy. The wave associated velocity increases with height until nonlinear effects, such as resonant interactions or wave breaking, take place. When this happens, energy and momentum carried by the wave may be deposited to the background atmosphere. It is currently believed, for example, that gravity waves play a key role in determining the general large-scale circulation in the middle atmosphere(18). In addition, a principal means by which the lower atmosphere couples with the thermosphere is through the dissipation of gravity waves, resulting in momentum and heat flux divergences and enhanced turbulent mixing. At high latitudes, energy input from the magnetosphere generates AGWs that propagate around the globe in the thermosphere(19), providing a possible channel for coupling of energy from high to low latitudes.

Analysis of ionospheric waves detected with GPS carrier phase measurements can yield a wealth of information about the processes giving rise to the waves and about the flow of energy within and among different earth systems. In the future, when suitable receivers are in orbit, we hope to detect and analyze individual wave events, identify the relation (or transfer function) between source events and the resulting gravity waves in the atmosphere, and estimate the energy and momentum input to the atmosphere from gravity waves. Through such studies we hope to understand clearly the generation and propagation of gravity waves due to all important sources, including magnetospheric auroral sources from above, and weather, orographic (winds over mountains), volcanic, seismic, and other sources from below; the different influences of these waves on the background atmosphere; and their role in the transport of energy throughout the earth system.

DISCUSSION & CONCLUSIONS

Ground-based observations are fundamental both as reference data in GPS-based POD and as primary data in geodynamics and ionospheric science. With the rapid advance of GPS receiver technology, we can expect within a decade to have geodetic quality receivers costing under $5000. The processing functions for tracking multiple satellites will be concentrated on a single chip. Receivers with ten or twelve dual frequency channels may soon become standard. Indeed, an argument can be made for providing two dozen channels in a dual GPS/Glonass receiver. Such an instrument would ensure continued full strength operation should one or the other satellite system become unavailable. Moreover, the greater data available when both systems are operating would improve geometric strength and provide roughly root-2 reductions in the error from data noise and multipath—possibly valuable in the pursuit of millimeter geodesy.

Perhaps more significant may be a reduction in the error from tropospheric delay. Imperfect calibration of tropospheric delay is one of the limiting errors in baseline measurements of more than a few tens of kilometers. Recent studies have shown that one of the most effective methods of calibrating the troposphere is to solve for both the wet and dry components with GPS observations themselves using carefully tuned stochastic models(5,6). This requires comprehensive sampling of the visible sky. Doubling the number of signal sources will double the sky sampling density and strengthen the tropospheric solution, possibly improving baseline results well beyond what might be expected from the simple increase in data volume. Greater sampling density may be particularly helpful when azimuthal asymmetry is incorporated into the troposphere models.

Selective availability and anti-spoof—the intentional degradation of system accuracy and encryption of the signal—are a continuing concern to scientific and civil GPS users. Happily, selective availability (SA), which may operate continuously, does not affect the ability of GPS receivers to track the satellites and acquire quality data. The positioning applications described here—both POD and ground geodesy—are inherently differential, employing precisely known reference networks. This permits the virtual elimination of SA effects in data analysis. The occultation applications are more problematical. Satellite differencing schemes are possible but not desirable; without such schemes, the potential degradation, if any, will depend upon the SA levels in effect. It is expected that information to remove SA degradation will be made available to general users after a respectful waiting period, perhaps a few weeks. For most scientific applications, this should be satisfactory.

Unhappily, anti-spoof (AS) will defeat any code-tracking receiver not privileged with the decrypting keys. Although it is widely expected that AS will be active only infrequently, the Department of Defense (DoD) advises that users should not depend on it. An alternative is offered by codeless receivers, which are unaffected by AS encryption. Although codeless receivers sacrifice measurement precision, in many uses data noise is not the major error and performance approaching the levels quoted here can be achieved. (Eos and the space station have stringent real time GPS requirements and will likely carry code-tracking receivers equipped to remove SA and AS.) It is possible, therefore, to pursue the range of GPS science presented here, in the full presence of SA and AS, without access to the classified keys—though perhaps with some inconvenience. There is one more prospect to consider: DoD has stated that the GPS performance available to general users will be no worse than the performance available by other means. With an open Glonass in the offing, and various commercial satellite positioning systems proposed, that could soon mean virtually no SA or AS at all.

GPS has already begun to transform a number of areas of earth science. This account of the emerging GPS role has been necessarily limited, but it touches most of the areas that show promise today. A decade from now we may be surprised by the number of developments unforeseen. With deployment of the first Block 2 satellites now imminent, we look forward to the transition from a time of growing anticipation to one of solid accomplishment.

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